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Experimental generation of volcanic lightning

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ABSTRACT

Explosive volcanic eruptions are commonly associated with intense electrical activity and lightning. Direct measurement of the electric potential at the vent, where the electric activity in the volcanic plume is first observed, is severely impeded, limiting progress in its investigation. We have achieved volcanic lightning in the laboratory during rapid decompression experiments of gas-particle mixtures under controlled conditions, and recorded it using a high-speed camera and two antennas. We find that lightning is controlled by the dynamics of the particle-laden jet and by the abundance of fine particles. The relative movement of clusters of charged particles generates the electrical potential, which is necessary for lightning. The experimental generation of volcanic lightning suggests that rapid progress can now be expected in understanding electrical phenomena in volcanic plumes to implement lightning monitoring systems and the forecasting of volcanic ash emissions.

INTRODUCTION

Lightning discharges are often observed during explosive volcanic eruptions and are commonly associated with the formation of ash plumes (Mather and Harrison, 2006; James et al., 2008; McNutt and Williams, 2010; Rakov and Uman, 2003). Their occurrence appears to be independent of magma composition, eruption type, and plume height (McNutt and Williams, 2010). Increasingly sophisticated lightning mapping arrays show that lightning discharges are ubiquitously produced within three regions of the plume, each of which is governed by very distinct dynamics, i.e., (1) the gas-thrust region immediately above the vent, (2) the convection-driven rising column extending several kilometers above the vent, and (3) the neutrally buoyant umbrella region (Thomas et al., 2010; Bennett et al., 2010; Behnke et al., 2013). At least two main regimes of electrical discharges have been described derived from lightning mapping array observations (Thomas et al., 2007, 2010; Behnke et al., 2013): (1) the vent discharges (sparks) and near-vent lightning, associated with the fragmentation of magma and collision of particles occurring during the explosion, and (2) the plume lightning, dominated by gravitational separation of the ejecta, occurring in the convective plume (Thomas et al., 2010; Behnke et al., 2013). Field studies of electric field variations induced by volcanic plumes have focused mainly on the convective and umbrella regions (Anderson et al., 1965; Lane and Gilbert, 1992; James et al., 1998; McNutt and Davis, 2000; Miura et al., 2002). Current models of electrical charging within the convective column propose that volcanic plumes may behave as "dirty thunderstorms," thus being able to produce lightning discharges as commonly observed in thunderstorms (Williams and McNutt, 2004; Thomas et al., 2007). As such, the presence of hydrometeors within the plume has been assigned a decisive role in the generation of volcanic lightning (Arason et al., 2011). Measurements of electrically charged volcanic ash in the field (Miura et al., 2002; Gilbert et al., 1991; Calvari et al., 2012) and in laboratory experiments (James et al., 2000; Büttner et al., 2000) invoke triboelectrification (electrification of solids through friction) and fractoemission (emission of electrons and ions from fresh crack surfaces resulting in a residual charge) as the main mechanisms of volcanic particle electrification (Gilbert et al., 1991; James et al., 2008). In previous experiments lightning discharges have not been observed, thus demonstrating that particle charging *per se* is a necessary but insufficient condition for lightning generation. Some important questions remain concerning volcanic lightning. How are lightning discharges generated in the near-vent region? What is the dominating mechanism for particle charging and electrical discharge at the inception of an explosive eruption? Does this mechanism depend on particle size distribution? Finally, if charging mechanism and charge distribution are key parameters for lightning generation, to what extent is the charging mechanism and charge distribution model proposed for thunderclouds (Rakov and Uman, 2003) valid for volcanic plumes?

METHOD

We generated lightning in rapid decompression experiments in a shock tube (Alatorre-Ibargüengoitia et al., 2011) (Fig. 1A). Upon decompression (from ~10 MPa argon pressure to atmospheric pressure P_a = 0.1 MPa), loose particles are vertically accelerated and ejected through a nozzle of 2.8 cm diameter (D) into a large tank filled with air at atmospheric conditions. Because of their impulsive character, our experiments most closely represent the conditions encountered in the gas-thrust region of the plume, when pyroclasts are first ejected from the crater. We used sieved natural ash with different grain sizes (Table DR1 in the GSA Data Repository[1]) from Popocatépetl (Mexico), Eyjafjallajökull (Iceland), and Soufrière Hills (Montserrat) volcanoes, as well as micrometric glass beads to constrain the influence of

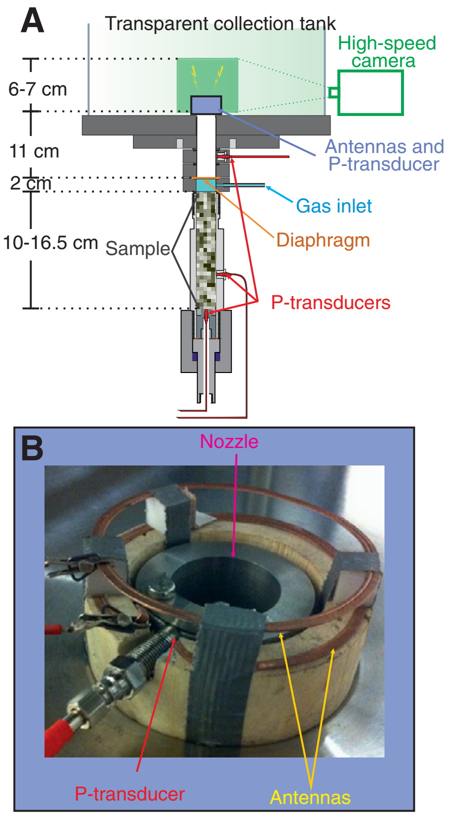

Figure 1. A: Shock-tube apparatus. B: Close-up of nozzle, pressure transducers, and antennas. Nozzle diameter is 2.8 cm, distance between antennas is 1 cm. Autoclave is filled with loose particles and equipped with pressure transducers. Gas-particle mixture is decompressed through diaphragm and ejected into collection tank (atmospheric pressure, P_a ~ 0.1 MPa, atmospheric temperature, T_a ~ 24 °C, relative humidity ~60%). All sensors are synchronized with high-speed camera recording at as much as 50,000 frames/s.

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[1] GSA Data Repository item 2014018, Table DR1 (experimental conditions), Figure DR1 (electronic schematics of the antennas), Figures DR2–DR5 (video frames of lightning flashes), and Videos DR1 and DR2 (high-speed videos of two experiments with different camera exposure time), is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

GEOLOGY
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material properties on lightning. We monitored the dynamics of the particle-laden jets with a high-speed camera and the pressure and electric potential at the nozzle using a pressure transducer and two copper ring antennas connected to a high-impedance data acquisition system, respectively (Fig. 1B; Fig. DR1).

EXPERIMENTAL RESULTS

High Speed Imaging and Electric Measurements

We distinguish three temporal phases within each experiment (Fig. 2): (1) the escape of the argon originally above the loaded particles; (2) the ejection of the front of the gas-particle mixture and the generation of a more turbulent conical region surrounding the main jet (turbulent shell); and (3) the ejection of the remaining particles in a well-collimated jet. In the first phase (Fig. 2B), the shock wave and the argon escape produce a sharp pressure increase, the gas condensation, and a negative transient in the electric potential relative to Earth. Experimental runs without particles only exhibit this negative electrical transient associated with the gas escape, and no electrical discharge is observed. Due to partial decoupling of gas and particles, a gas fraction escapes ahead of the mixture front, generating an additional pressure peak and a second negative electric transient. In the second phase (Fig. 2C), corresponding to the first arrival of particles, the pressure at the nozzle increases. The overpressure at the nozzle leads to an unconfined expansion of the gas-particle mixture and generates a turbulent shell around the core of the flow (Ogden et al., 2008). Observed flashes and related electrical discharges are generated exclusively during this second phase (lasting 6–9 ms) and clearly correlate with the overpressure at the nozzle and the presence of the turbulent shell (Fig. 2A). Frequent smaller potential changes characterize the beginning of this phase, which evolves to less frequent, higher voltage discharges. During the third phase, particles are ejected for a further 200–250 ms: the pressure at the nozzle rapidly decreases to P_a, the electric potential recovers the initial value, no turbulent shell is observed, and no further discharges are recorded.

In one experiment, the antennas can record hundreds of electrical discharges (amplitude >0.2 V, duration 0.6 µs) associated with flashes to 5 cm in length (Figs. DR2–DR5). High-speed videos (Videos DR1 and DR2 in the Data Repository) show that most of the flashes originate and propagate within a region defined by the turbulent shell and a 2 *D* vertical distance above the nozzle. This distance is consistent with the theoretical Mach disk height for a pressure of ~6 P_a at the vent (Ogden et al., 2008). As is the case for thundercloud lightning, we also observe in our experiments downward- and upward-propagating flashes associated with both positive and negative discharges, as recorded by shape and polarity of spikes in the potential signal.

We observe that more discharges are generated for finer starting material (Table DR1) and that there is no correlation between number of discharges and ash chemistry. We also observe that finer ashes produce higher number of discharges and that nonwashed samples generate more discharges than their washed counterparts. This is likely due to the presence of very fine ash shards on the surface of nonwashed coarser particles. Nevertheless, the componentry (glass ± crystals ± lithics), density, and shape of ash particles from a single eruptive event can vary widely with grain size. Shape and density changes affect the drag force and therefore will influence the fluid dynamic properties of the particles, especially with regard to the coupling to the gas phase, and thereby control the mean distribution of particles in the jet near-field. These factors are likely to influence the charging mechanism of particles in the experiments and in nature.

Effect of Grain-Size Distribution on Discharge Number and Flow Structure

The spherical glass beads, used in this study as a standard material, are highly homogeneous in density, chemistry, and shape, independent of size. The response of a particle in a flow is characterized by its Stokes number $S_k = \tau_p/\tau_f$, where τ_p is the time required for a particle to obtain a velocity of 63% of the fluid velocity, and τ_f is a characteristic flow time scale. It has been shown that particles with $S_k >> 1$ are unresponsive to fluctuations within the flow and that preferential clustering of particles first occurs when $S_k \approx 1$ in regions of relatively high strain and low velocity (Longmire and Eaton, 1992). As a first-order approximation, τ_p can be expressed in terms of the particle diameter using the Ergun (1952) equation. In our experiments, $\tau_f \sim 0.6$ ms, and therefore $S_k = 1$ corresponds to particles between 60 µm for volcanic ash and 100 µm for glass beads. For time scales of a few seconds, expected in volcanic eruptions, $S_k = 1$ corresponds to clasts between 500 and 1000 µm, i.e., in the size range of volcanic ash. Notably, almost no discharges are produced during experiments with monodisperse coarse beads (500 µm, $S_k >> 1$). With increasing weight percent of fines (50 µm, $S_k \approx 1$), the number of discharges increases proportionally (Fig. 3A). We also observe that the structure of the jet changes accordingly with the addition of fines.

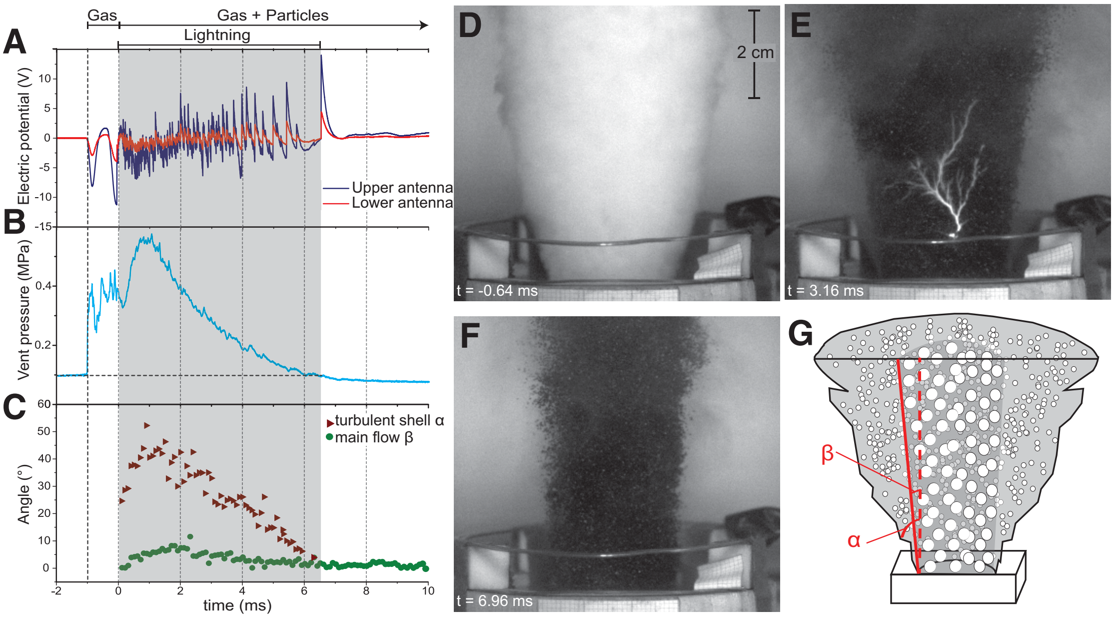

Figure 2. Decompression experiment with 250 µm Popocatépetl ash. A: Electric potential recorded by antennas. B: Pressure at nozzle. C: Angle of core flow (β) and turbulent shell (α) to vertical. Shaded area shows time of flash occurrence. D–F: Consecutive phases of experiment. D: Condensing argon before particle ejection (t = time). E: Turbulent shell surrounds particle-laden jet and flashes are recorded. F: Turbulent shell is no longer visible, discharges stop, gas-particle mix is further ejected in collimated flow. G: Schematic section of jet, showing flow core (coarse particles, dark gray), turbulent shell (fine particles, light gray), and respective opening angles β and α.

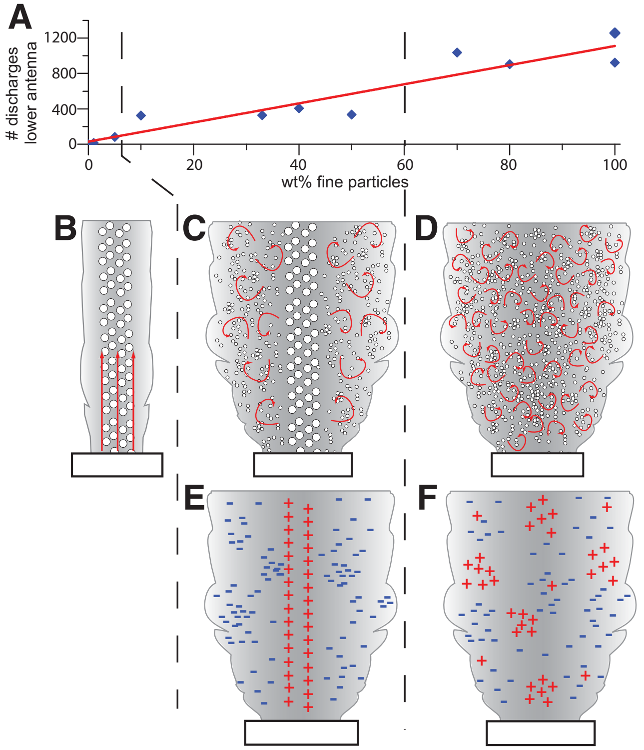

Figure 3. Discharge generation and dependence on grain size. A: Number of discharges >0.2 V recorded by lower antenna in experiments with bimodal glass beads (500 and 50 µm) as function of weight percent of fines. Stokes number (S_k) differs by ~2 orders of magnitude between two particle types. B: Monodisperse coarse beads form collimated flow and no lightning occurs. C: In bimodal blends, coarse beads ($S_k \gg 1$) are at core of flow and fines ($S_k \approx 1$) form turbulent shell. D: Monodisperse fine beads move according to local flow turbulence. E: For bimodal blends, coarser particles tend to have relative positive charge with respect to Earth, whereas smaller particles tend to charge negatively. Their different responses to fluid dynamics provide mechanism for charging and charge separation according to grain size. F: For monodisperse fine particles, transient clustering with different relative charge density provides necessary gradient for discharges (in E and F, positive and negative symbols represent relative charge density, not necessarily different polarity).

MECHANISM OF LIGHTNING GENERATION

High-speed videos show that for monodisperse 500 µm beads ($S_k \gg 1$), particle motion is dominated by inertia so that the flow is well collimated above the nozzle and particle-particle interaction (hence charging) is negligible (Fig. 3B). On the contrary, for monodisperse 50 µm beads ($S_k \approx 1$), particles are small enough to be coupled with the gas and are affected by local turbulence. In turbulent regions, particles form clusters (Ogden et al., 2008), thus promoting collision and triboelectrical charging (Fig. 3D). Glass spheres did not macroscopically fragment during particle-particle collisions, but since fractoemission acts at the molecular scale, we cannot exclude that microscale spalling might contribute to particle charging. For bimodal blends the flow structure is transitional between the two monodisperse end members. Relative motion of particles according to their S_k enhances charging by collision. Self-charging of glass beads in fluidized beds is well documented (Lowell and Truscott, 1986; Pähtz et al., 2010), and tribological studies with bimodal populations demonstrate the tendency of relatively smaller beads to charge negatively while relatively larger ones charge positively (Lacks and Levandovsky, 2007). In bimodal blends inertia forces the coarse particles in a well-collimated flow at the core of the jet while fine particles are radially accelerated by the expanding gas to the periphery to form the turbulent shell (Fig. 3C), providing an efficient mechanism for charge separation and electrical discharge (Fig. 3E).

We thus propose that the formation of transient clusters is crucial for electrical discharges in monodisperse fine particle jets (Fig. 3F). Clusters form and break up by densification and rarefaction of the particle-laden jet. A cluster's lifetime is regulated by the turbulence time scale and its modification during the evolution of the flow (Burton and Eaton, 2005). In addition to the radial acceleration of particles by the expanding gas, cluster generation and disruption provide the necessary conditions for particle electrification by collision, local concentration of charges, and consequent separation, thus creating the electric potential gradient necessary to generate electrostatic discharges. Our experiments show that the frequency and amplitude of the discharges are inversely related (Fig. 2A), meaning that the potential between clusters increases with time according to the changing length scale of the flow (with expansion collisions become less frequent and clusters are progressively more distant from each other).

In a very similar fashion, during impulsive explosion at Sakurajima volcano in Japan, frequent and shorter discharges are observed near the crater concomitant to the explosion, while longer and more luminous lightning discharges are observed tens of seconds after (Aizawa et al., 2010), when the plume is hundreds of meters high and expanding by convective intake of air (e.g., 8 February 2010 eruption; Smithsonian Institution National Museum of Natural History Global Volcanism Program, 2010). We observed these two modes of lightning occurrence during recent vigorous eruptive episodes (14–24 July 2013) at Sakurajima. It should be noted that, even during the 19 July episode, where the column reached a maximum height of 6100 m above sea level (a.s.l.) (according to the Tokyo Volcanic Ash Advisory Center), the ash never reached the isotherm –20 °C, which during those days was measured well above 8000 m a.s.l. (Japan Meteorological Agency, http://www.jma.go.jp/jma/indexe.html), thus excluding the presence of ice in the column.

SUMMARY

Ash-rich volcanic plumes, e.g., 2010 Eyjafjallajökull (Iceland) eruption (Bennett et al., 2010; Taddeucci et al., 2011) and the ash-rich Vulcanian explosions at Stromboli (Italy) (Calvari et al., 2012) and Sakurajima (Aizawa et al., 2010), often produce lightning. Our experiments are consistent with this observation and further reveal a direct relation between the number of electrical discharges and the abundance of ejected fine particles. We propose that clustering of particles provides an efficient mechanism for both charge generation and lightning discharge within volcanic plumes. Clustering can be particularly effective in the presence of prevalently fine ash–laden jets exiting the volcanic conduit. Further charging by magma fragmentation, convection, and buoyancy of particles in the upper regions of the plume, along with the formation of hydrometeors, may provide additional mechanisms of plume electrification.

Our experiments open a new perspective in the investigation of volcanic lightning generation with emphasis on the plume's gas-thrust region, where electrical discharges are first observed. We anticipate that high-speed camera observations synchronized with magnetotelluric, Doppler radar, and lightning mapping array measurements will ensure further advances in our understanding of electrification processes at active volcanoes. We believe that such improved lightning monitoring has the potential to provide first-hand information not only on the location of the eruption and the structure of the plume but, more important, on the presence and amount of fine ash ejected, a fundamental input in ash-dispersion forecast models. Furthermore, our experiments are significant for the investigation of self-charging mechanism of particles that are relevant for atmospheric phenomena on Earth (such as dust storms and mesocyclones) and other planetary bodies, and industrial processes involving granular materials.

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